/ATTACHMENT

Statement of Problem

The broad objective of this work has been to extend our understanding of the nature of the conventional or classical hybrid rocket combustion process (fuel decomposition, heat and mass transfer, and chemical reaction), and the critical engineering parameters that define this process. As an assistance in the development and verification of CFD models of the hybrid combustion process, specific objectives were to bound the relative proportions of radiative and convective heat transfer to the fuel surface in the developed boundary layer region and to determine the pyrolysis law for hydroxyl-terminated polybutadiene (HTPB) under hybrid rocket heating conditions.

Scope and Methods of Approach

An existing hybrid slab window motor (Figure 1) was instrumented with several diagnostic techniques per the respective test configurations shown in Figure 2. Configuration A permitted heat flux measurements with a calorimeter (total) and radiometer (radiation component). Configurations B and C used IR pyrometry to measure the core gas temperature and the combusting fuel surface temperature. Configuration B allowed high-speed digital video coverage of the combusting slab entrance region. Tests with a non-metalized HTPB fuel were carried out over a range of motor pressure and GOX oxidizer mass flux conditions. The time averaged fuel regression rates were determined by both before and after measurement and weighing of the fuel slabs.

The measured results were compared with predictions from a hybrid fuel combustion model developed earlier.[1]

Summary of Important Conclusions

Similarities observed between motor chamber pressure and measured total heat flux support the earlier postulation that the driving mechanism for the observed low-frequency, sub-acoustic pressure oscillations is some type of flow-combustion turbulence interaction along the surface of the propellant slab.

Any model of the hybrid motor ignition process will have to be able to describe the progression of the fuel surface temperature-time profile, as observed in these experiments.

The c* efficiencies determined from the test results for this motor peaked near the stoichiometric O/F point.

The measured convective heat flux was in reasonable agreement with calculations based on the measured motor chamber gas temperature.

The measured radiation flux was considerably higher (factor of two) than predictions based on the measured gas temperature. This is believed to be due to the large, unaccounted for contribution from the cloud of fine, particulate free-carbon burning in the gas stream.

For a given regression rate, the measured fuel surface temperatures were somewhat higher, by approximately 12-13Y0, than literature pyrolysis data for HTPB.[3] A possible explanation of this difference is the different concentrations of Thermax carbon powder filler contained in the HTPB for the two studies, 0.25% and 3°A respectively. The higher literature value would provide greater assurance that the HTPB was opaque to radiation heat transfer.

Statement of Data Used

Figure 3 compares typical total heat flux and chamber pressure profiles for a test firing at a head end, time-averaged oxidizer flux of 4.36 gm/cm^2-s (0.062 lbm/in^2-s). The mean O/F ration was 2.4. Both traces exhibit oscillations at a frequency of approximately 5 Hz. The phase lead of the chamber pressure oscillations is undoubtedly due in large part to the much better time response (factor of approx. 100) of its measurement system.

Figure 4 compares the measured total and radiation heat flux traces **for** the test. The smoothness of the latter is, of course, due to its insensitivity to irregularities in the gaseous fluid flow.

Figure 5 shows typical measured core gas and fuel surface temperature-time profiles for a test firing at a head end, time-averaged oxidizer flux of 5.30 gm/cm^2-s (0.075 lbm/in^2-s) and mean O/F ratio of 1.7. The, null (no input) readings for the two IR pyrometers are 2000°F and 600°F respectively. Following ignition of the fuel, the igniter is shut off and oxidizer flow is initiated at t=0.5 sec. Chamber pressurization and fuel surface temperature rise continue until approximately 1.5 sec. The Figure 4 radiation heat flux closely tracks the core gas temperature profile, as is to be expected.

Figure 6 is a plot of c* efficiency vs. O/F ratio for the higher pressure tests, 1.2 - 1.4 MPa (170 - 200 psi), showing a maximum near the stoichiometric O/F ratio. Lower pressure tests were less efficient.

The calculated and measured convective and radiation heat flux components are compared in Figures 7 and 8 respectively, showing considerably better agreement for the former.

The measured pyrolysis results are compared with literature data for HTPB in Figure 9.

References

1. Strand, L. D. , Ray, R. L., and Cohen, N.S.,, ."Hybrid Rocket Combustion Study," AIAA 93-2412, 29th Joint Propulsion Conference, Monterey, CA, June 1993.

2. Cohen, N.S. and Strand, L. D., "Hybrid Propulsion Based on Fluid-Controlled Solid Gas Generators," AIAA 93-2550, 29th Joint Propulsion Conference, Monterey, CA, June 1993.

3. Cohen, N. S., Fleming, R. W., and Derr, R. L., "Role of Binders in Solid Propellant Combustion," AIAAJ.., Vol. 12, No. 2, February, 1974, pp. 212-218.

FIGURE 1

HYBRID SLAB WINDOW MOTOR

JPL

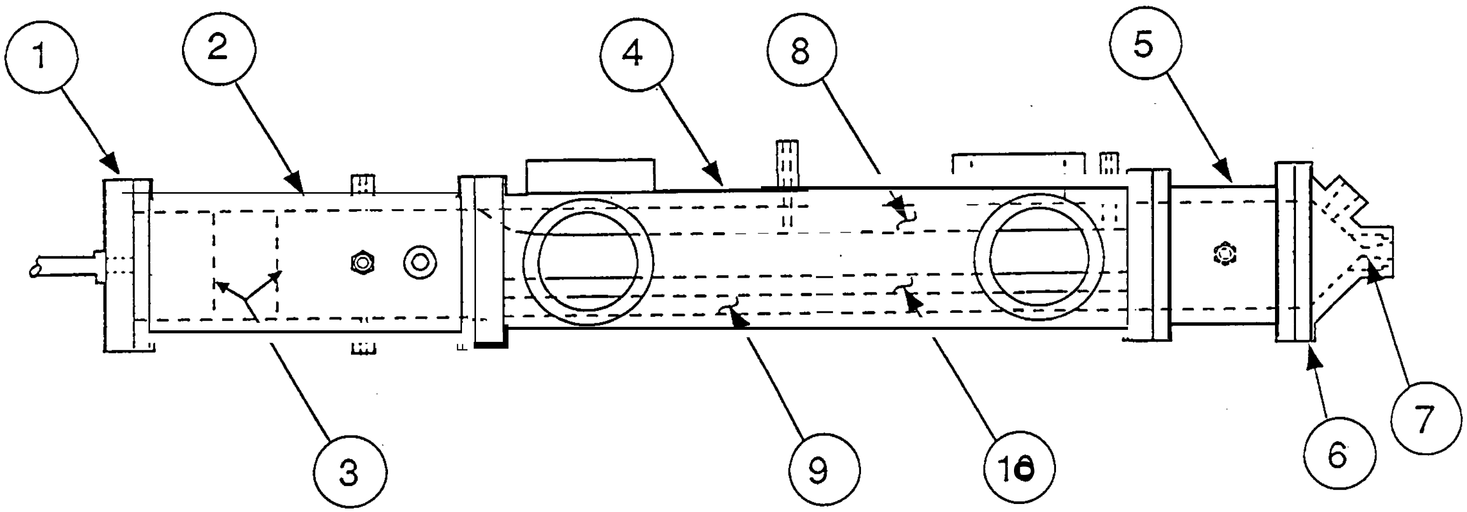


FIGURE 2

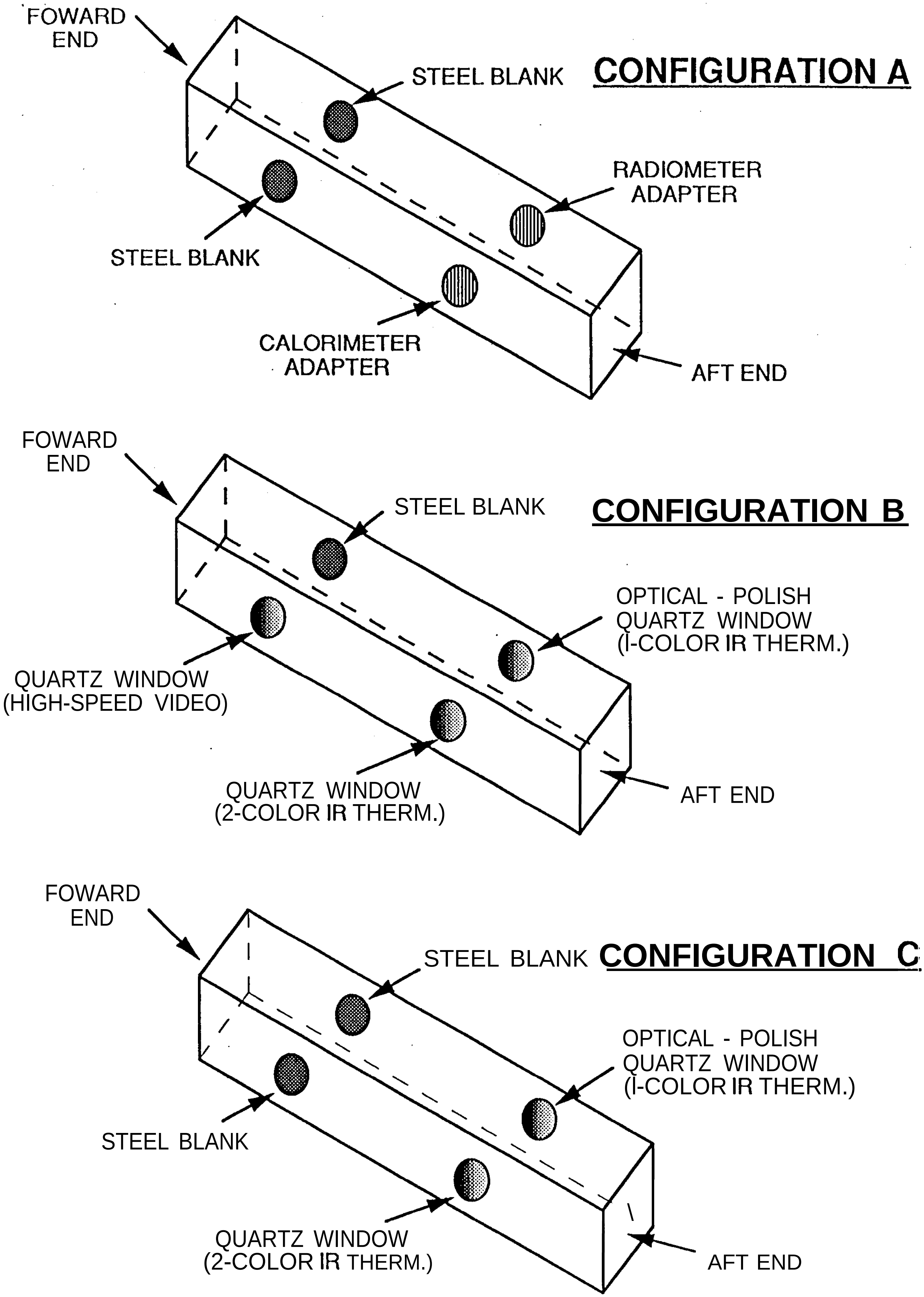

FOWARD END
STEEL BLANK
CONFIGURATION A
RADIOMETER ADAPTER
STEEL BLANK
CALORIMETER ADAPTER
AFT END
FOWARD END
STEEL BLANK
CONFIGURATION B
OPTICAL - POLISH QUARTZ WINDOW (l-COLOR IR THERM.)
QUARTZ WINDOW (HIGH-SPEED VIDEO)
QUARTZ WINDOW (2-COLOR IR THERM.)
AFT END
FOWARD END
STEEL BLANK
CONFIGURATION C
OPTICAL - POLISH QUARTZ WINDOW (l-COLOR IR THERM.)
STEEL BLANK
QUARTZ WINDOW (2-COLOR IR THERM.)
AFT END

FIGURE 3

HEAT FLUX & PRESSURE vs TIME

TEST NO. E2078 FUEL: HTPB

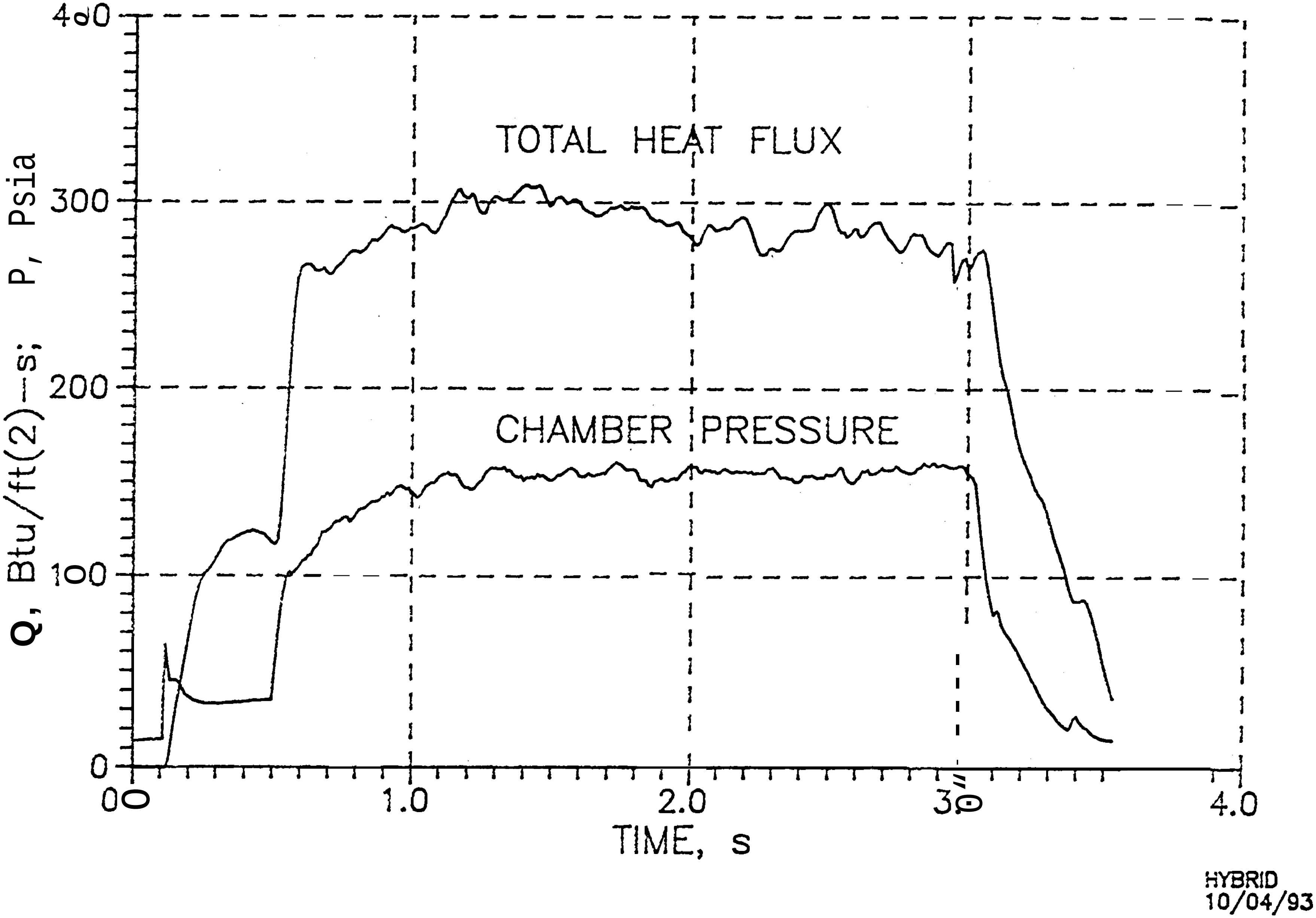


FIGURE 4

HEAT FLUX VS TIME

TEST NO. E2078 FUEL: HTPB

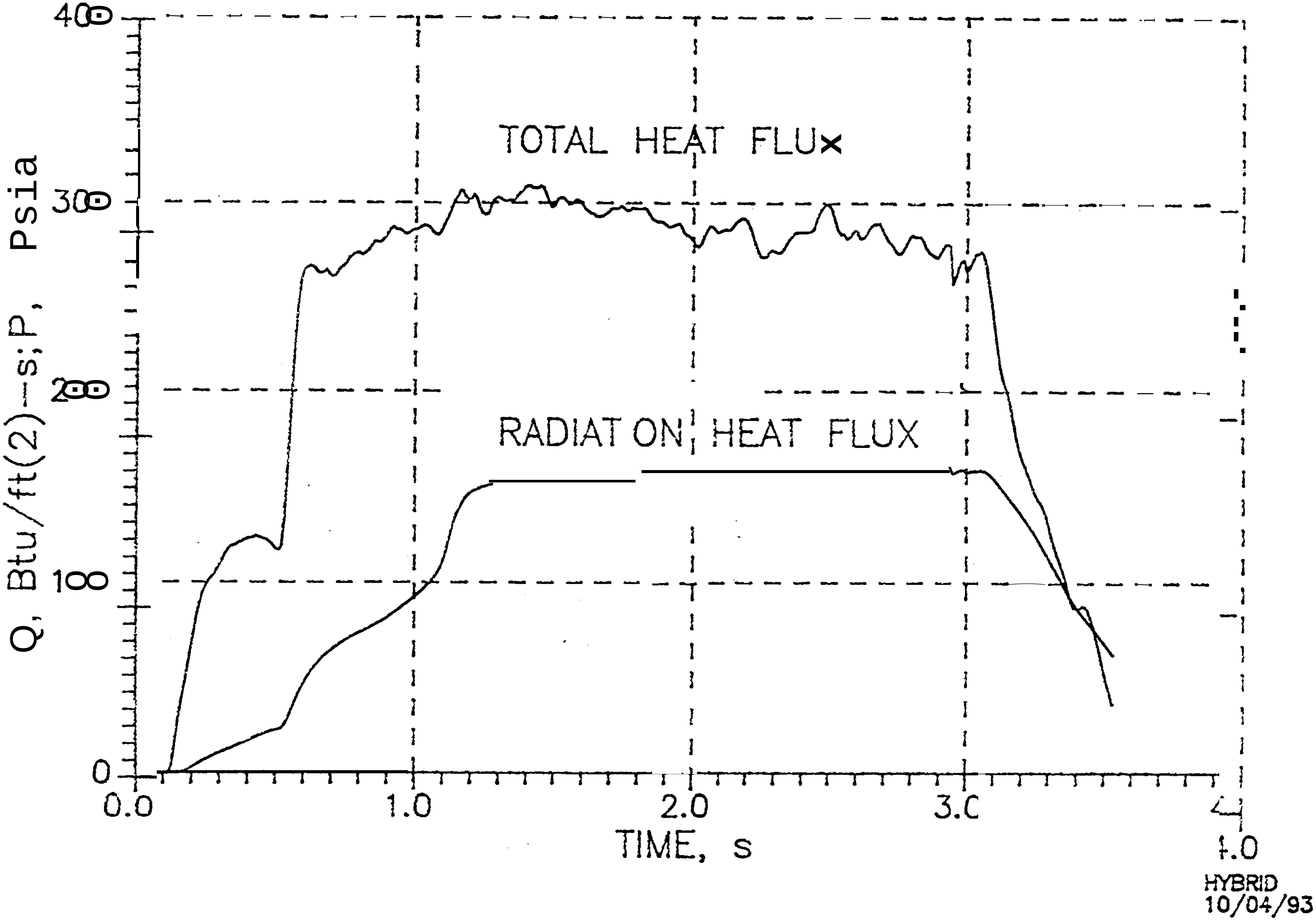


FIGURE 5

TEMPERATURE vs TIME

TEST NO. E2082 FUEL: HTPB

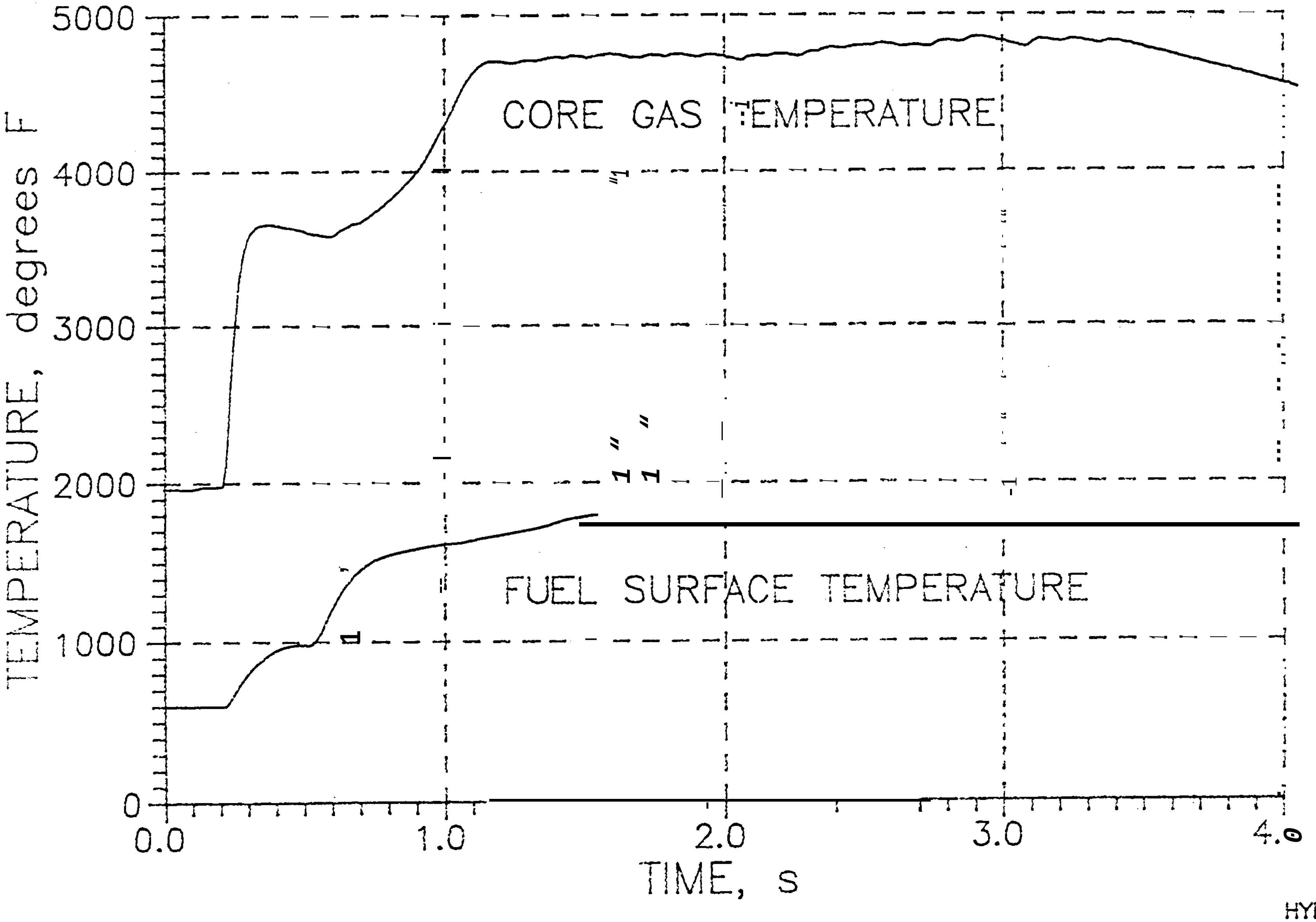


FIGURE 6

C* EFFICIENCY VS O/F RATIO
FOR HIGHER PRESSURE TESTS

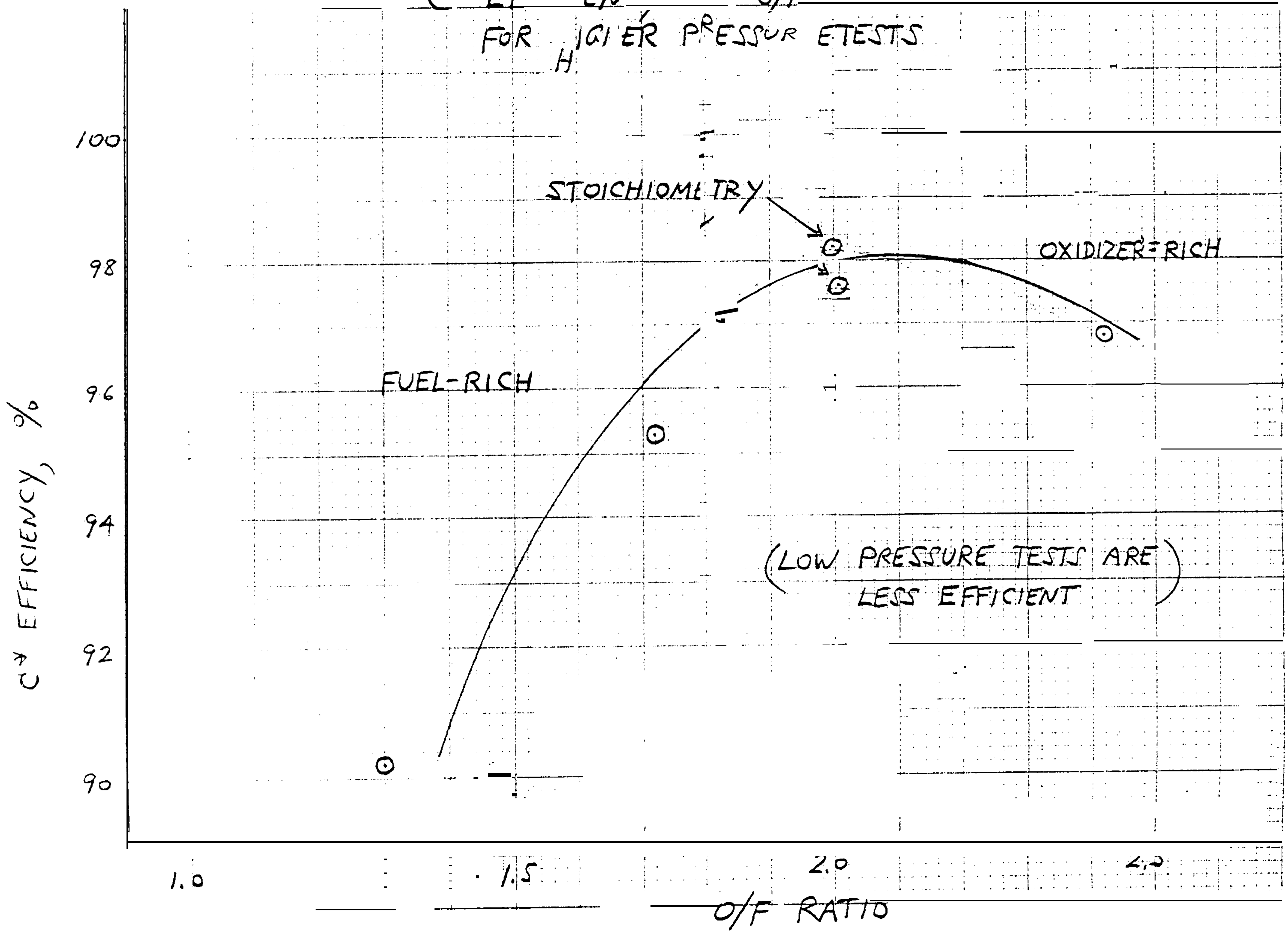
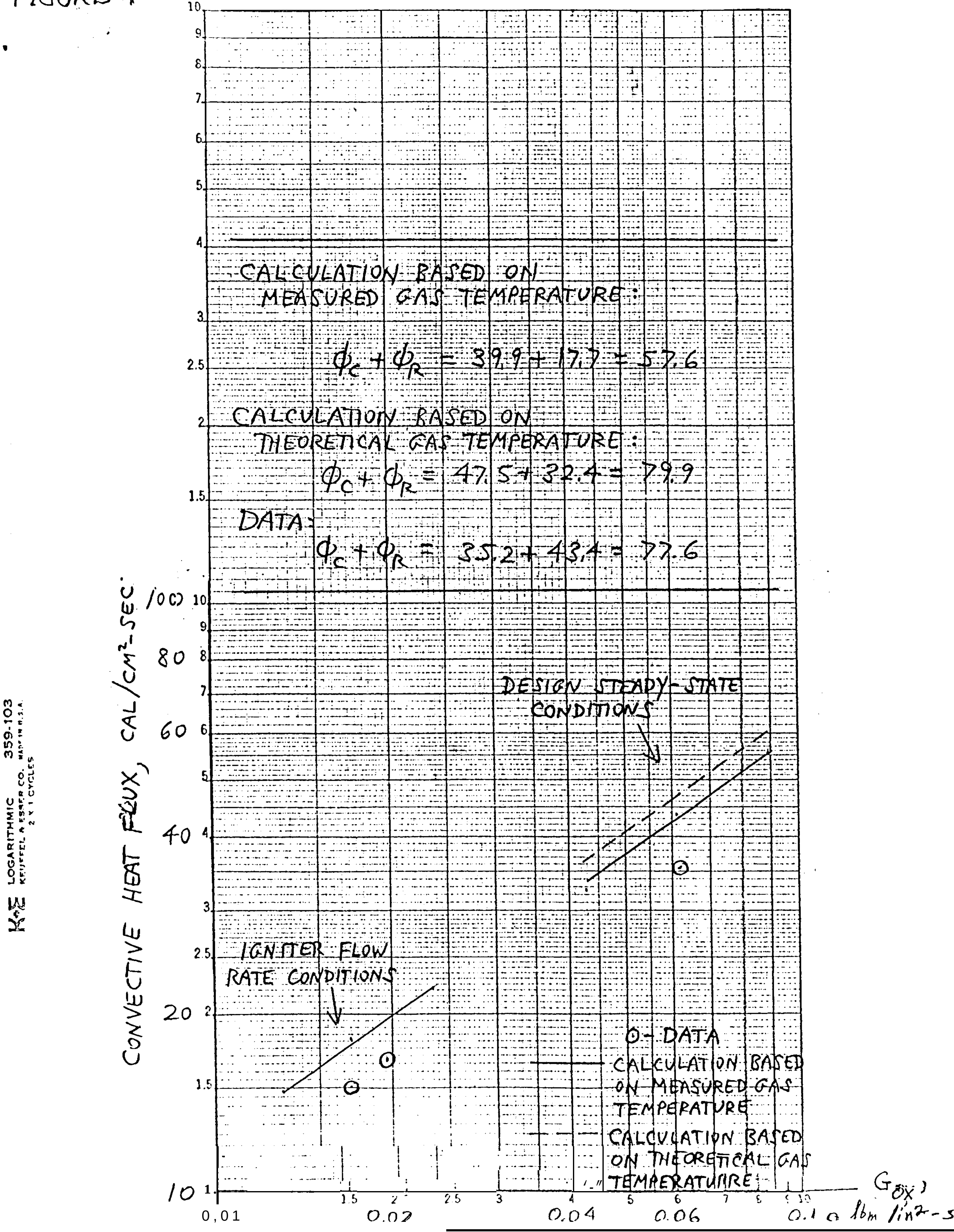


FIGURE 7

CALCULATED AND MEASURED CONVECTIVE HEAT FLUX



K+E 10 X 10 TO ½ INCH 7 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A. 46 1326

FIGURE 8

CALCULATED AND MEASURED RADIATION HEAT FLUX

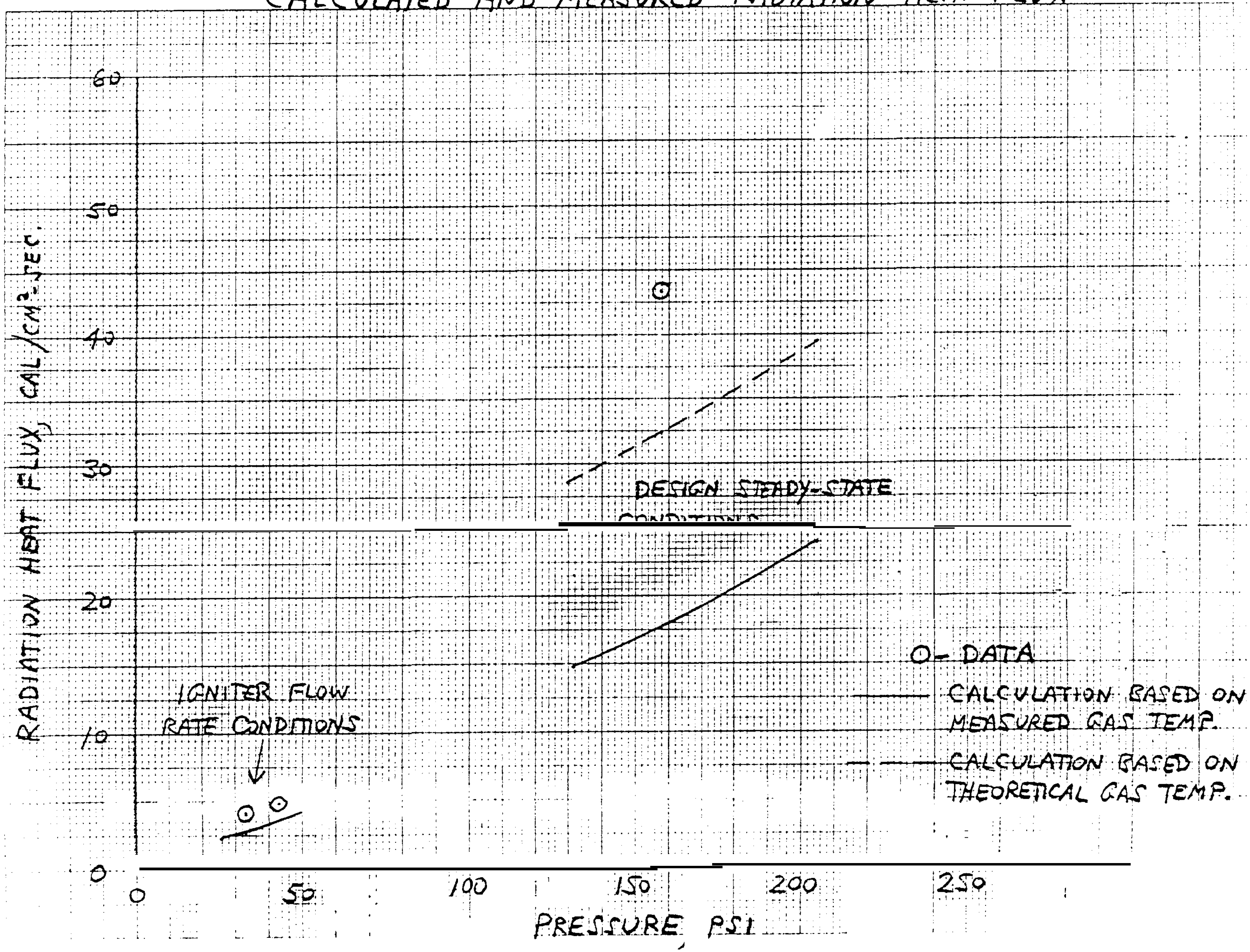
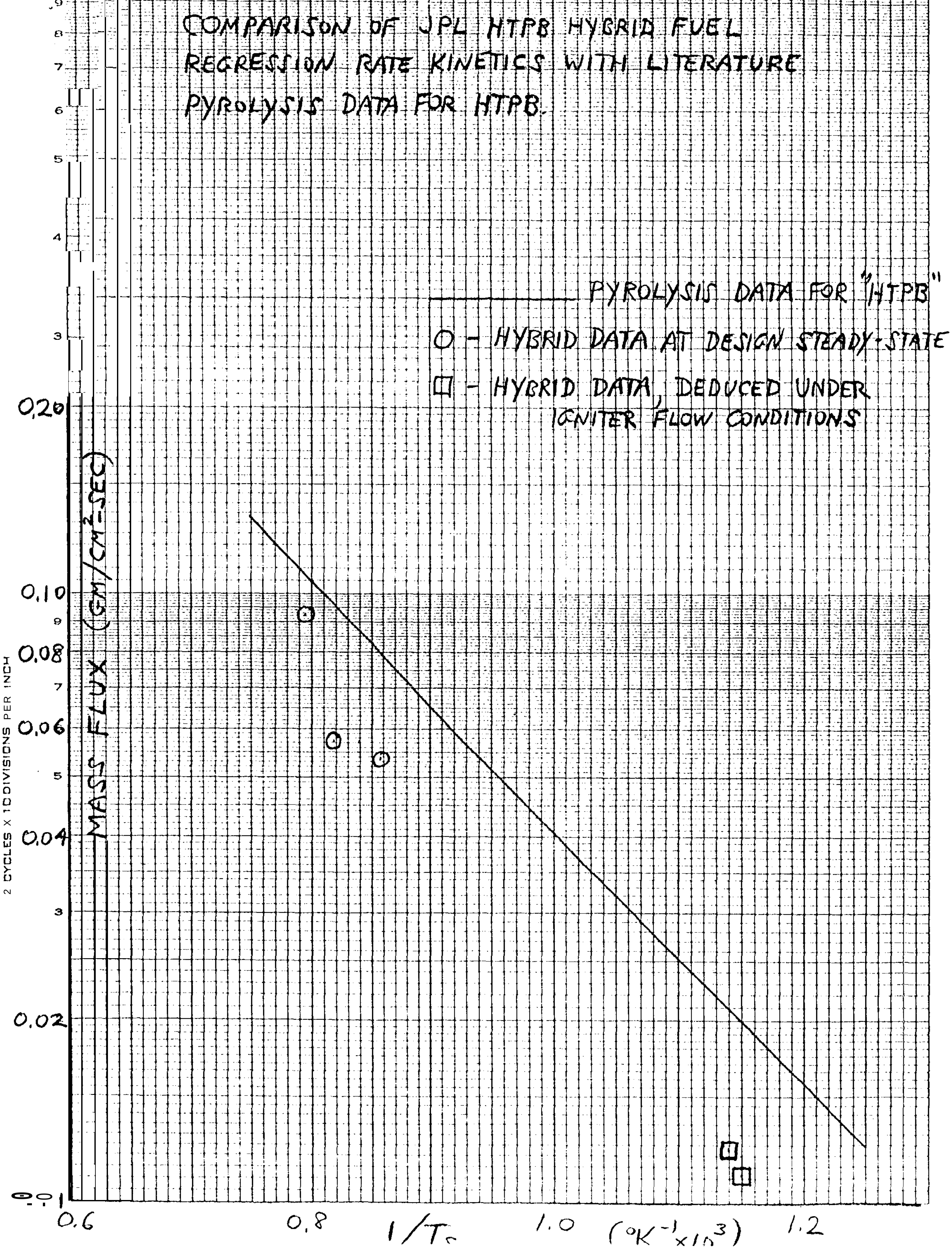


FIGURE 9



COMPARISON OF JPL HTPB HYBRID FUEL REGRESSION RATE KINETICS WITH LITERATURE PYROLYSIS DATA FOR HTPB.
PYROLYSIS DATA FOR "HTPB"
O - HYBRID DATA AT DESIGN STEADY-STATE
□ - HYBRID DATA, DEDUCED UNDER IGNITER FLOW CONDITIONS
MASS FLUX (GM/CM²-SEC)
0.20
0.10
0.08
0.06
0.04
0.02
0.01
0.6
0.8
1.0
1.2
1/Ts (°K⁻¹ x10³)